15295

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Evaluation of an Ice Detection System for NASA's Space Shuttle Missions

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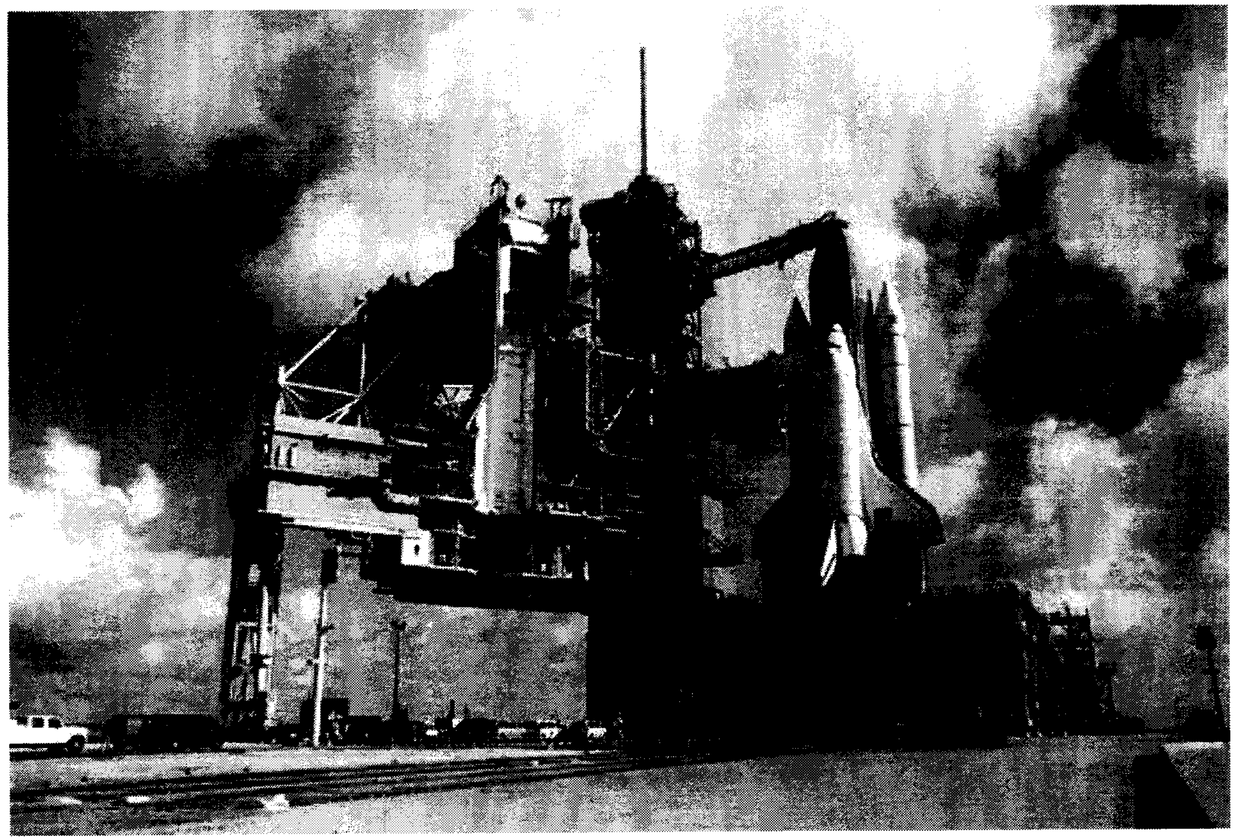
NASA/TARDEC Space Act Agreement

- Mutually beneficial research agreement between NASA-Kennedy Space Center (KSC) and US Army TARDEC (SOW entitled: "Ice/Frost Detection and Evaluation") signed 21 January 2004.

- NASA benefits: multi-spectrum sensor analysis and research for ice detection, orbiter tile evaluation, etc.

- Army benefits: applications to ice detection for wing/rotary aircraft, vehicle remote damage assessment, etc.



Space Shuttle Anatomy Basics

- The Space Shuttle is comprised of 3 main components: orbiter, ET, and 2 SRBs

- Two SRB's provide 80% of the thrust to launch the vehicle (jettisoned after 2 min., 28 naut. miles altitude - recovered)

- The ET houses liquid cryogenic fuel to supply the orbiter's 3 main engines (ET jettisoned after 8½ minutes, 70 miles altitude - not recovered)

External Tank (ET)

Solid Rocket Booster (SRB) (one on ea. side)

Orbiter

Orbiter Main Engine

Photo courtesy of NASA

ET Basics

- Manufactured at NASA-Michoud, New Orleans by Lockheed Martin

- Aluminum construction

- 154 ft. long, 28 ft. diameter

- Acts as the "backbone" of the Shuttle during launch supporting SRB and orbiter thrust loads of 7.8 million lbs.

- 33 tons (empty), 800 tons loaded

- Basically, a large fuel tank for the orbiter's 3 main engines

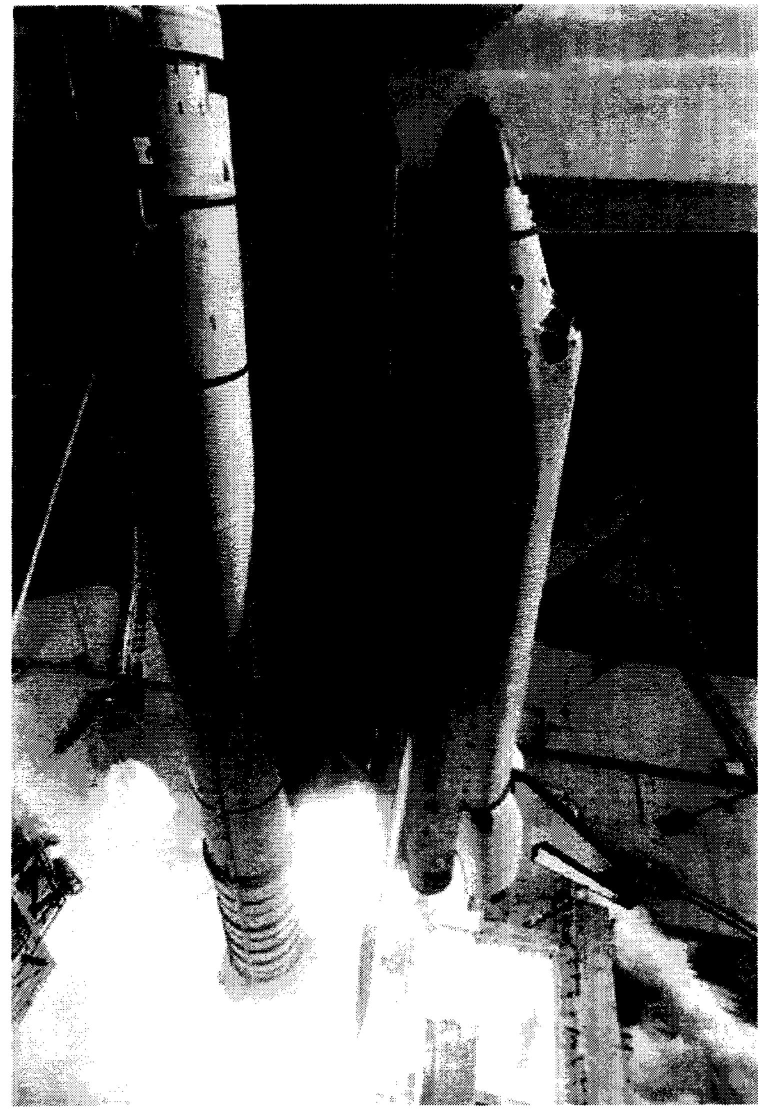


Photo courtesy of NASA

ET Basics continued...

- 3 main components

- Forward tank section holds 145,000 gals. of liquid Oxygen (-297 °F)

- Center intertank houses instrumentation and supports forward SRB thrust beam fittings

- Aft tank holds 309,000 gals. of liquid Hydrogen (-423 °F)

- Outer Al skin covered with thermal spray-on foam insulation (SOFI)

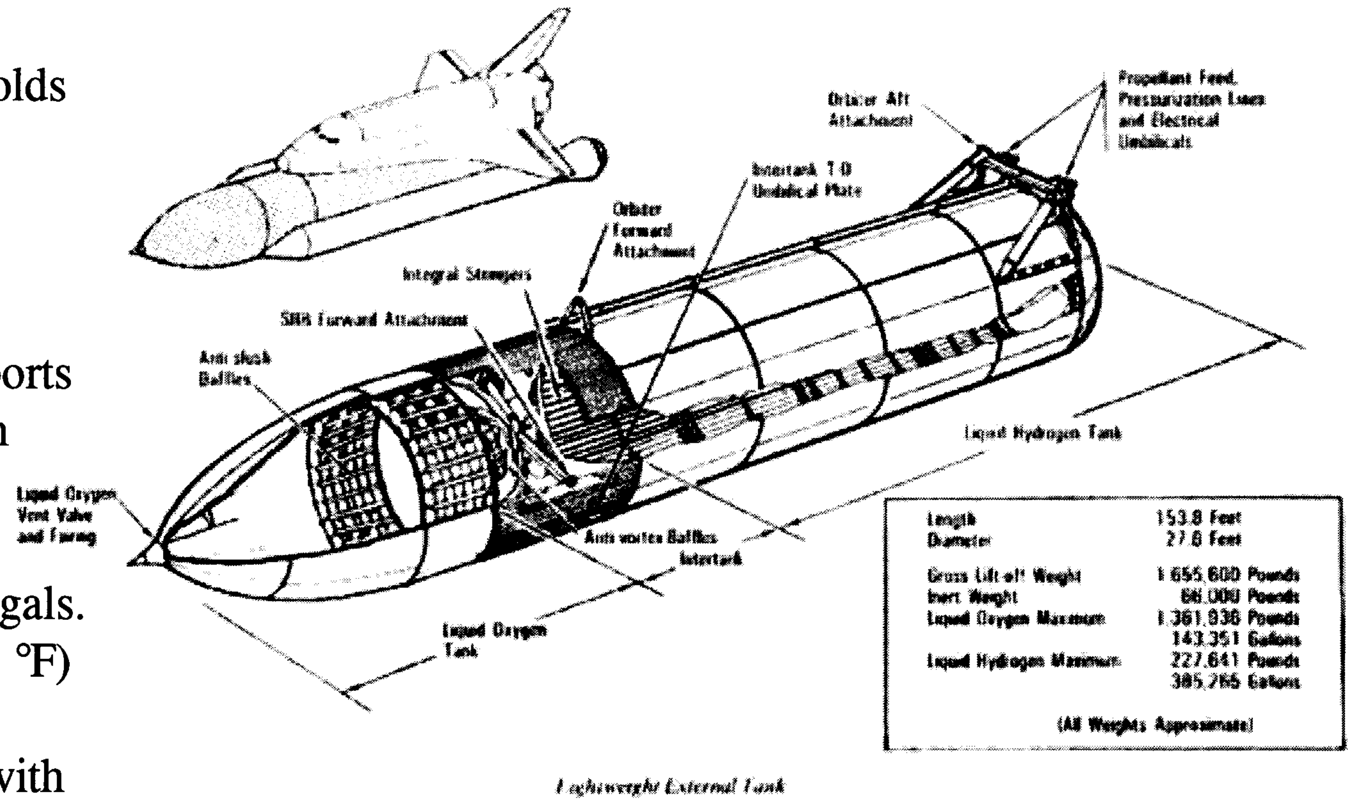


Diagram courtesy of NASA

ET Spray-On Foam Insulation (SOFI)

- Ranging from only 1-2 inches thick it is able to keep the cryogenic fuels LO2 (-297 °F) and LH2 (-423 °F) cold and minimize frost formation
- Adds 4,823 lbs to the ET's weight
- Made of a polyurethane-type foam it is primarily sprayed on robotically
- Starting out yellow in color, SOFI darkens as it is exposed to sunlight
- Some composite material Super Lightweight Ablator (SLA) is used in high temperature areas (near engine exhaust)

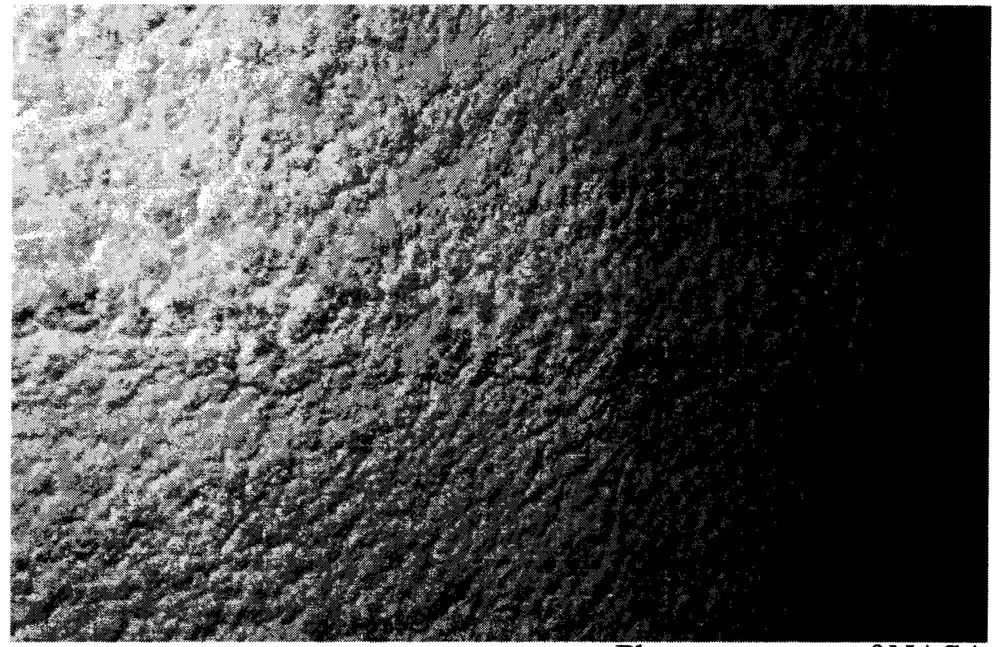


Photo courtesy of NASA

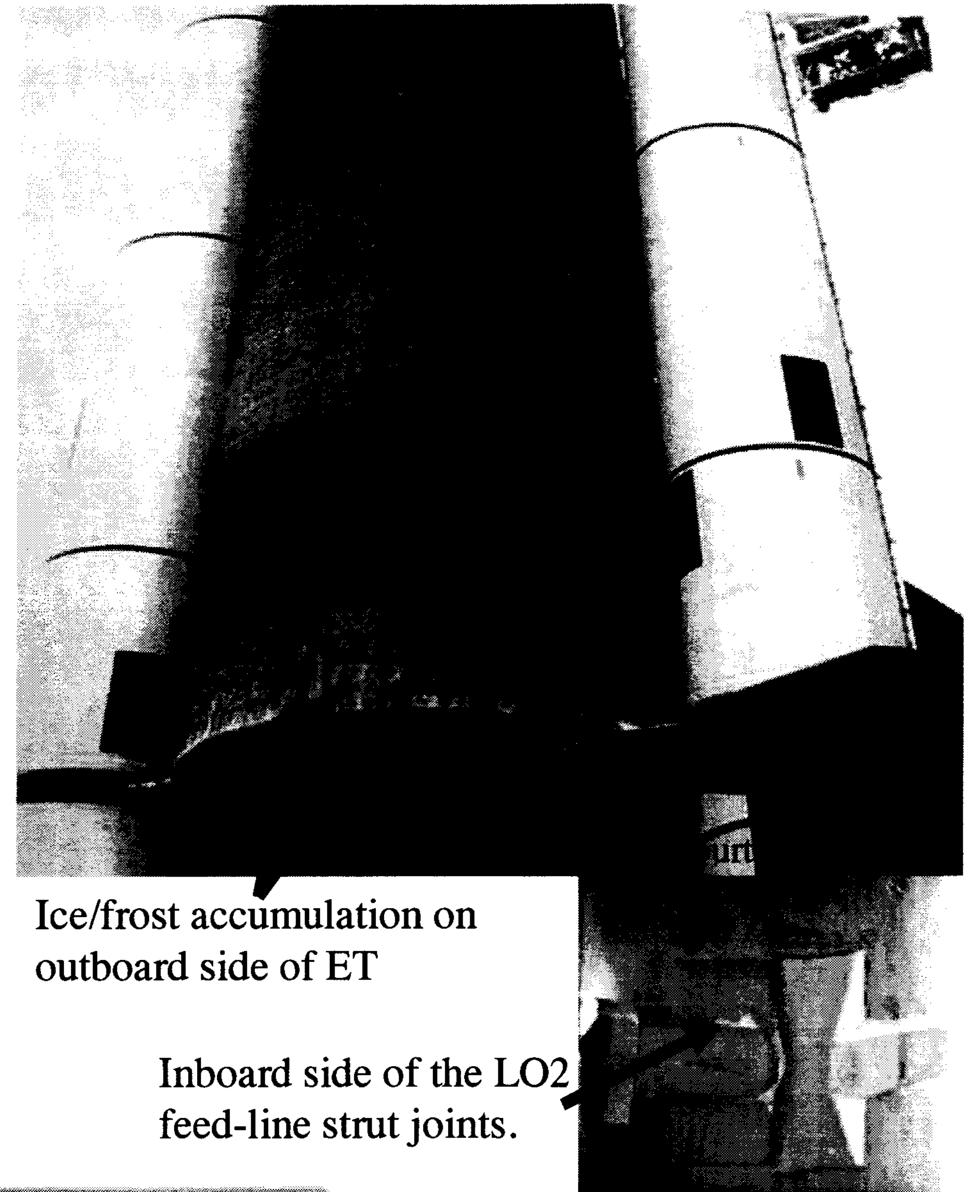
- SOFI must endure a 180-day stay on launch pad, temperatures of 1200 °F (generated by aerodynamic friction and rocket exhaust), 100% humidity, resist sand, salt, fog, rain, solar radiation, fungus, and even birds

ET Ice Accumulation

- After cryogenic fuel is added frost and ice may accumulate when ambient temperature drops below ~50 °F

- This has been a problem since the first shuttle flights

- Launch commit criteria (LCC) specifies a no-go situation when ice of size 1 inch dia. x 1/16 inch thick is found on specified areas of the ET due to its potential for causing damage during liftoff to the crew compartment windshield or orbiter thermal protection panels/tiles

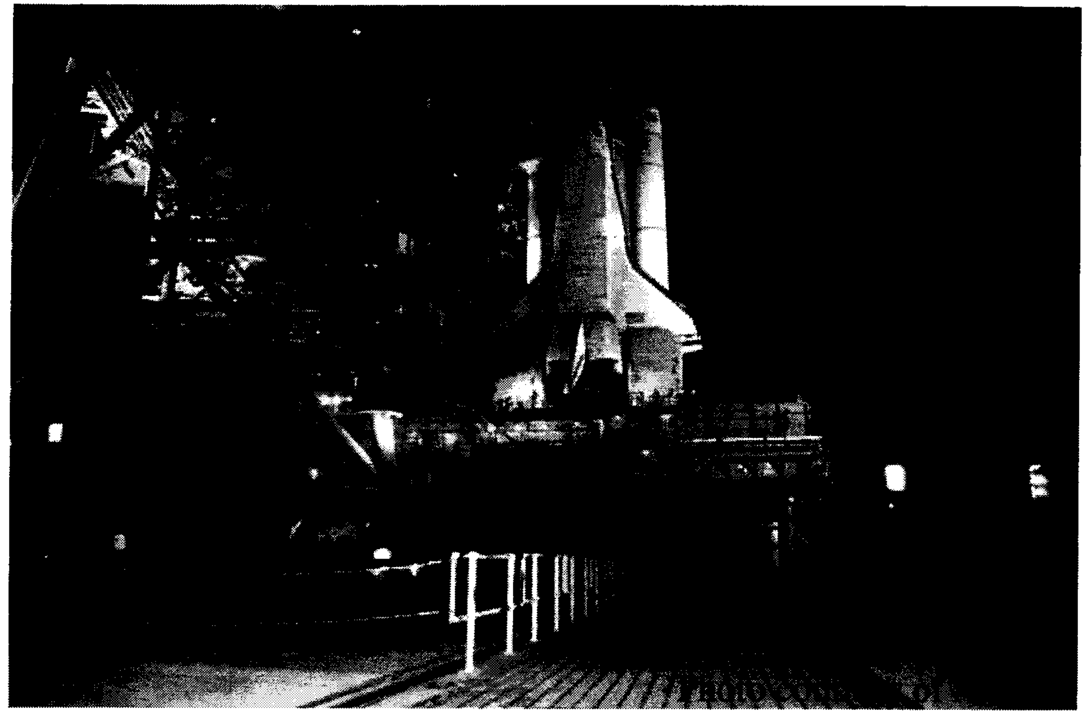


Ice/frost accumulation on outboard side of ET

Inboard side of the LO2 feed-line strut joints.

Ice Detector Specifications

At T-3 hours prior to launch, the NASA-KSC Ice Detection team performs a walk-down inspection of the launch pad



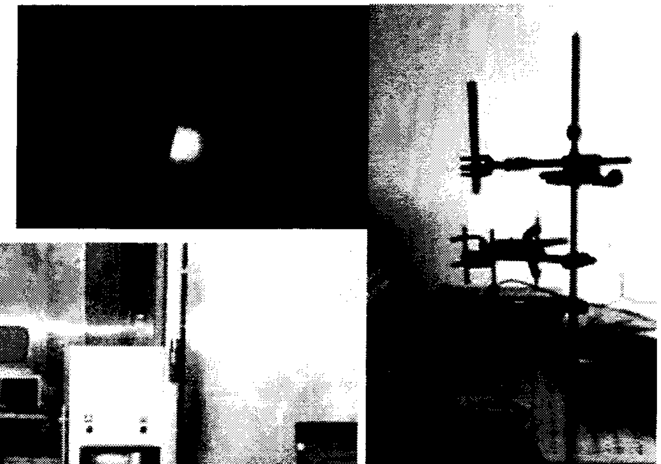
- Unit should be portable with a range of 25-125 feet (additional stationary units may be located at select sites at 80 and 1200 feet from the vehicle)
- Unit should have no EM emissions (for shuttle system's protection)
- Unit should be able to discern frost (defined as <18 lb/ft^3 density) from ice (≥ 18 lb/ft^3)
- Detect ice on ET acreage $\geq$ 1 inch dia. x 1/16 inch thick (about the size of a US quarter)
- Function at an angle 70° from surface normal

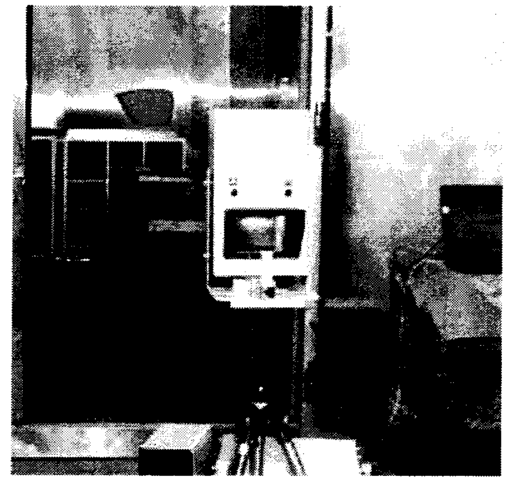
Technology Survey for Ice Detectors

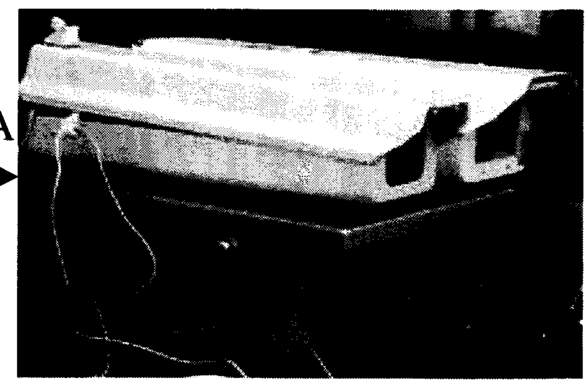
- National Research Council of Canada (NRCC) system utilizes a low power laser:
  - good ice thickness accuracy
  - required transparent ice – no frost
  - laser is non-passive

- Goodrich's IceHawk™ system, currently used by airline industry, utilizes near IR polarized light:
  - good ice/frost detection
  - required painted SOFI
  - could not measure ice thickness

- MacDonald, Dettwiler and Associates LTD (MDA) system senses near IR from Xenon strobe:
  - ice presence/thickness estimation


NRCC laser system


Goodrich IceHawk™


Early MDA system

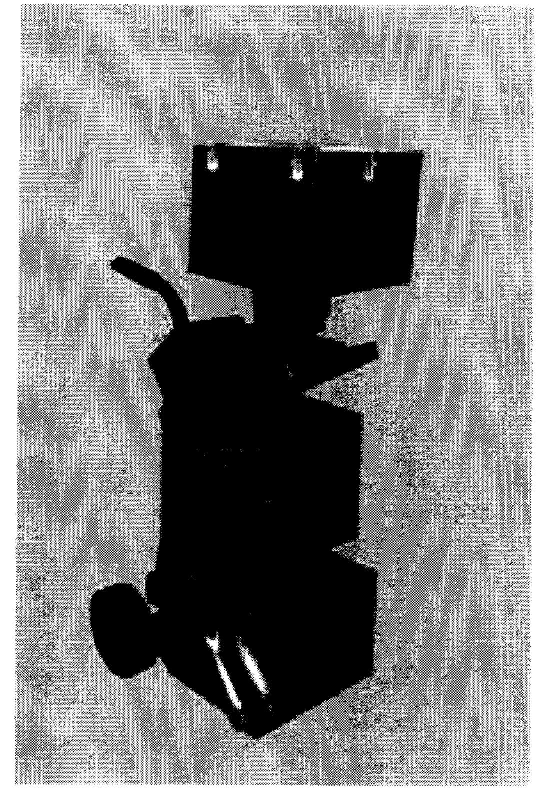
MDA System

- MDA system showed the most promise
- Contract was let to MDA for prototype system development requiring portability, range from 25-75 feet, positive pressurized containment for use on launch pad

- Prototype developed in about six months

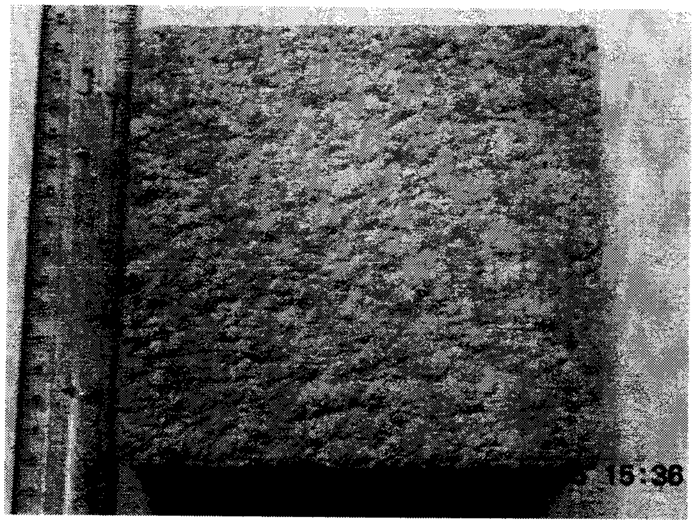
- 2nd battery of experiments designed to further test the system prior to Return to Flight use:

    - Test for frost/low density ice detection
    - Test for water/ice discernment
    - Test for range independency
    - Ice thickness estimation accuracy

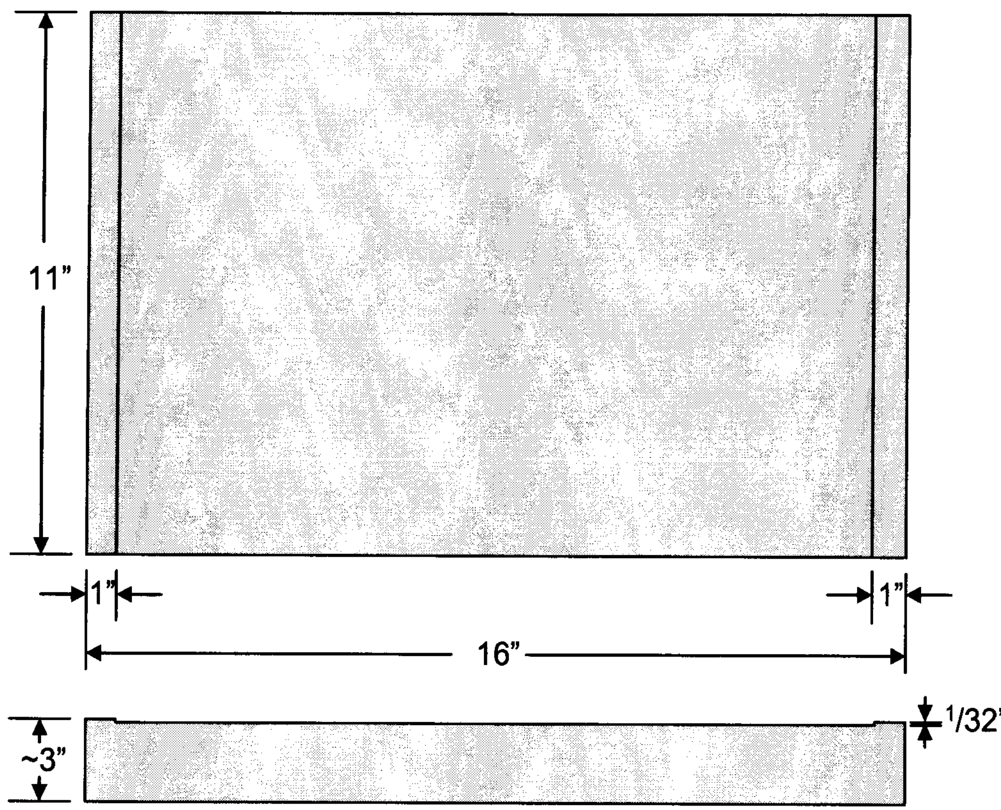


MDA current prototype

Test samples

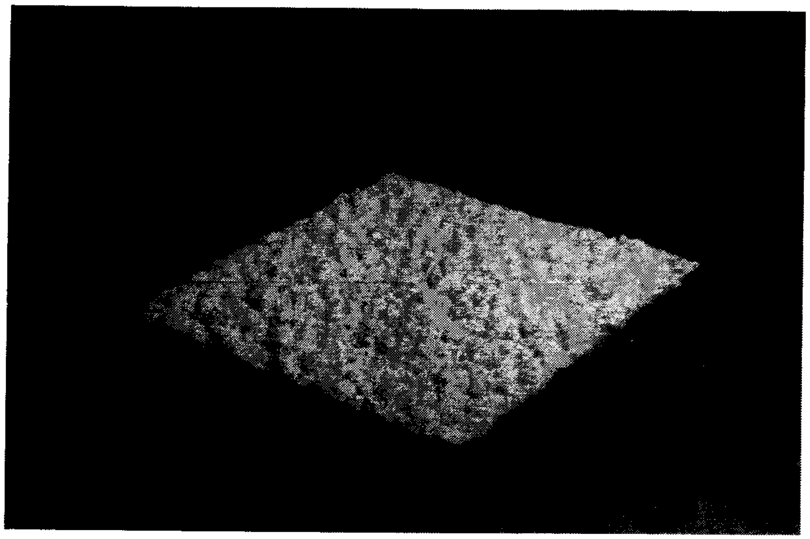


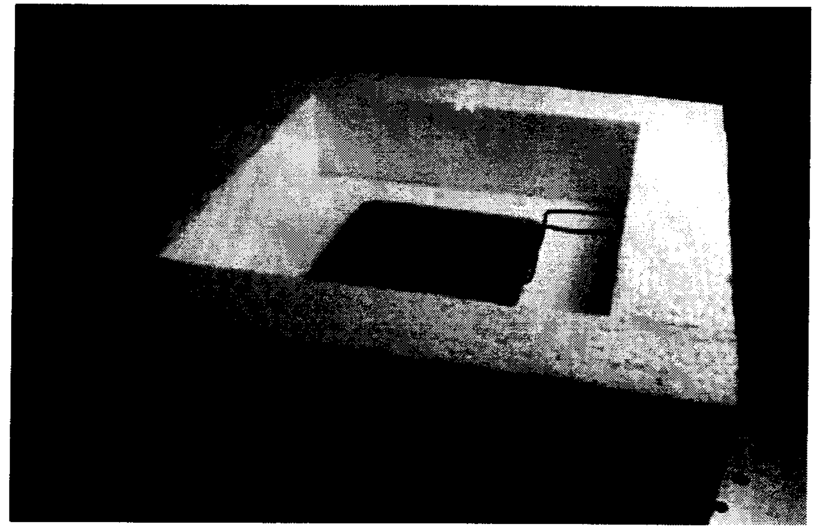
Typical natural SOFI surface top view showing surface roughness

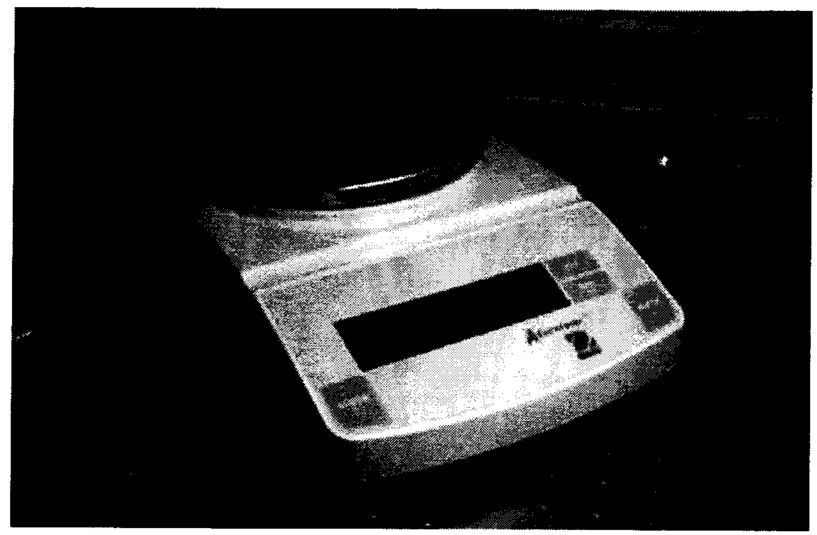


Large SOFI Milled

Frost / Ice Density

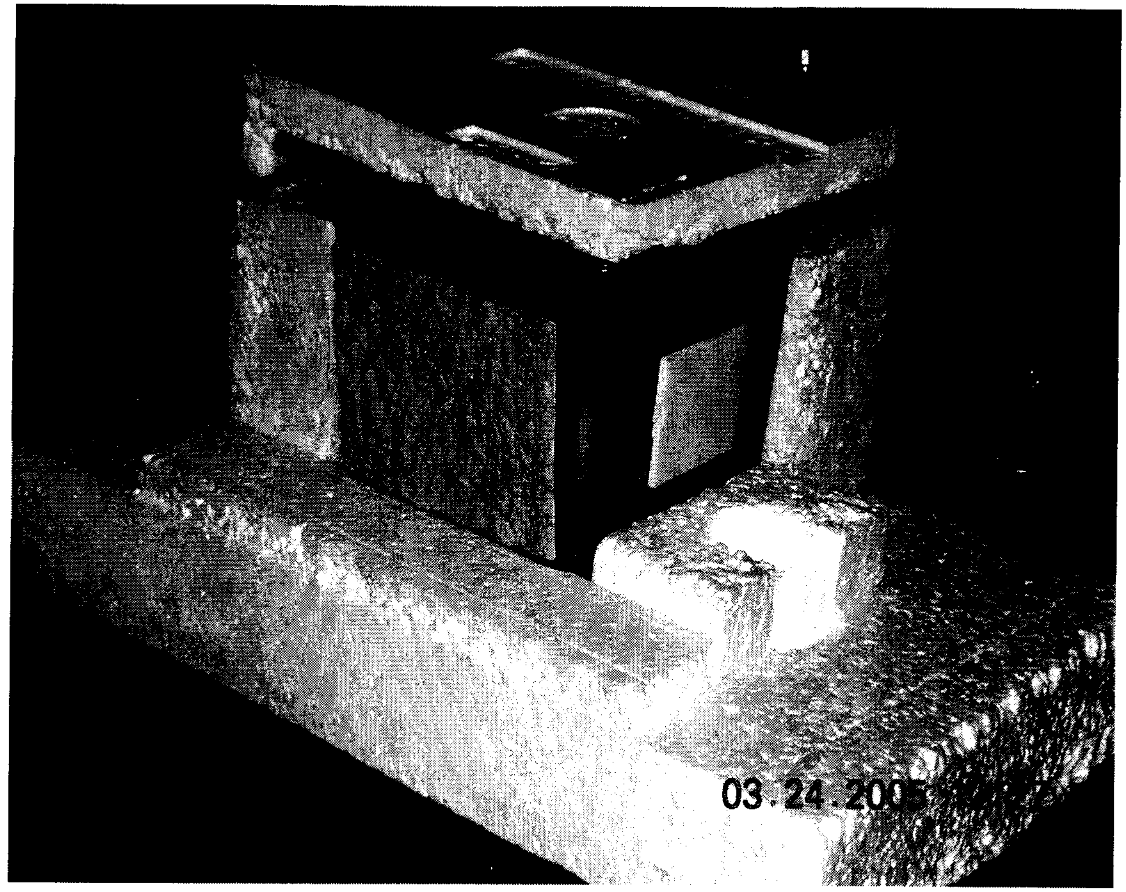






Goal 1: Detection of low-density ice (LDI) and comparison with results for normal density ice (NDI)

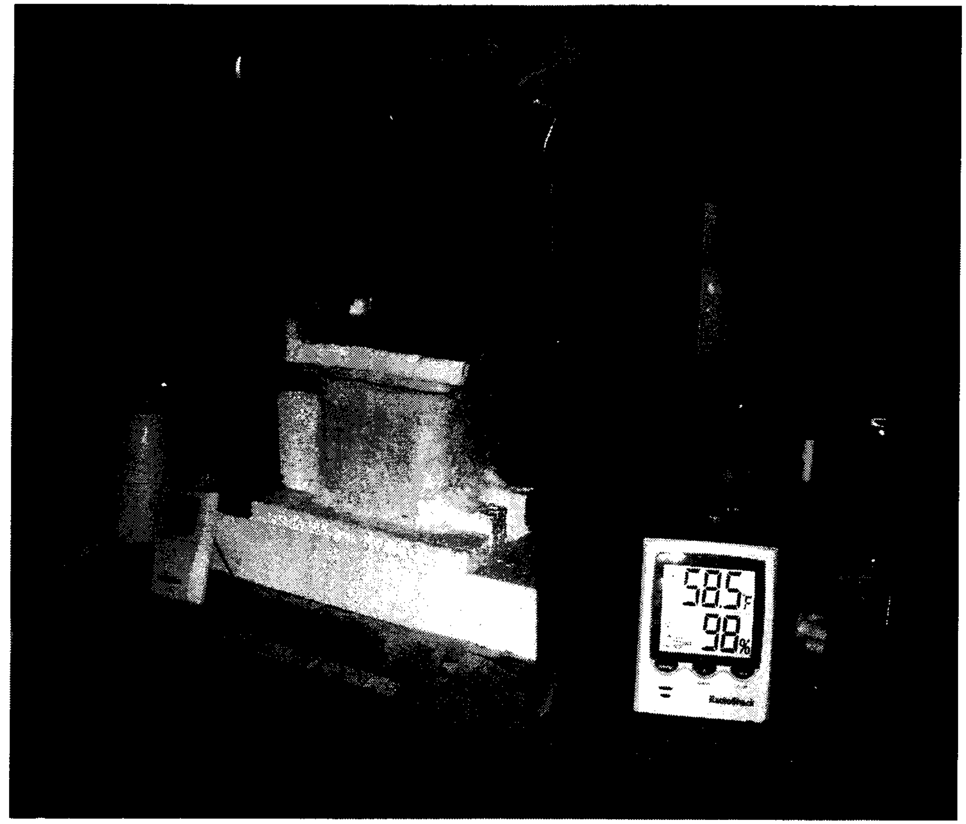
- The density of the ice buildup on the ET at KSC has been in the range of 18-37 lb/ftP3.
- Ice/frost with density < 18 lb/ftP3P does not pose a threat to the LCC it may be ignored.
- Typical ice formation (as in a freezer) is normally about 57 lb/ftP3.
- LDI will grow on a thin section of LN2 cooled ET foam sample under room or modeled humidity conditions.
- The test set up shown simulates ice growth that occurs on the full scale ET foam after the cryogenic fuel has been added.



Thin SOFI samples attached to LN2 test container

Goal 1: Detection of LDI and Frost (continued)

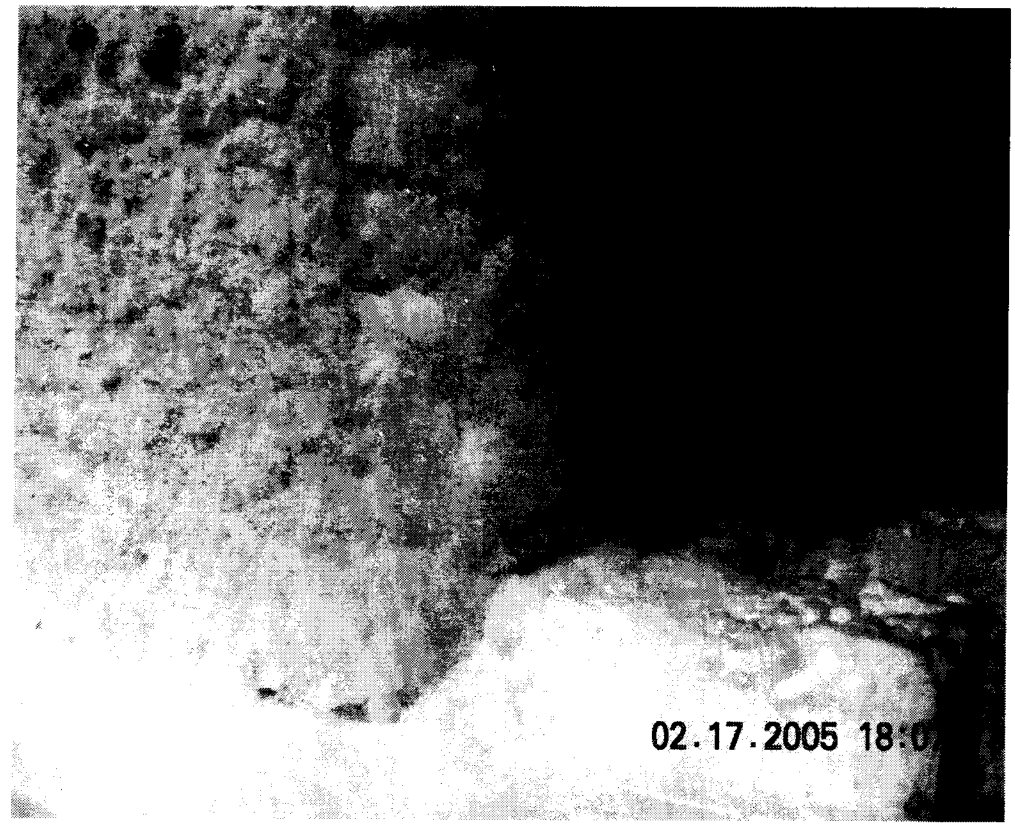
- Higher humidity seems to be required to make ice densities higher-than-frost.
- The laboratory humidity was low (21%).
- A cardboard box with one open side (for viewing) was placed over the entire test apparatus to make an enclosed environment
- The inside of the box and the open side was sealed with plastic sheeting (6 mil) to form a water barrier to keep the humidity from wicking out through the cardboard and into the atmosphere.
- A small ultrasonic type humidifier was placed inside the box.
- These modifications proved to consistently yield a humidity of about 98%.



Environmental chamber setup

Goal 1: Detection of LDI and Frost (continued)

- Liquid Nitrogen was poured into the container.
- Condensing water from higher ET SOFI acreage was thought to trickle down to colder areas and then freeze.
- This is believed to be, at least partially, the reason that the low density ice (18-37 lb/ftP3) was found on the ET and not the very low density ice/frost, (< 11 lb/ftP3).
- The combination of frost and ice may add in such a way to give a lower density ice measurement.
- Therefore, water was applied onto the SOFI samples periodically throughout the test so that it would freeze on the surface.
- Water was applied by spraying from a spray bottle directly at the samples.
- This finally proved to yield the “crunchy” ice mixed with frost (see Figure 7 below), and LDI densities in the desired range described by NASA scientists (18-37 lb/ftP3).

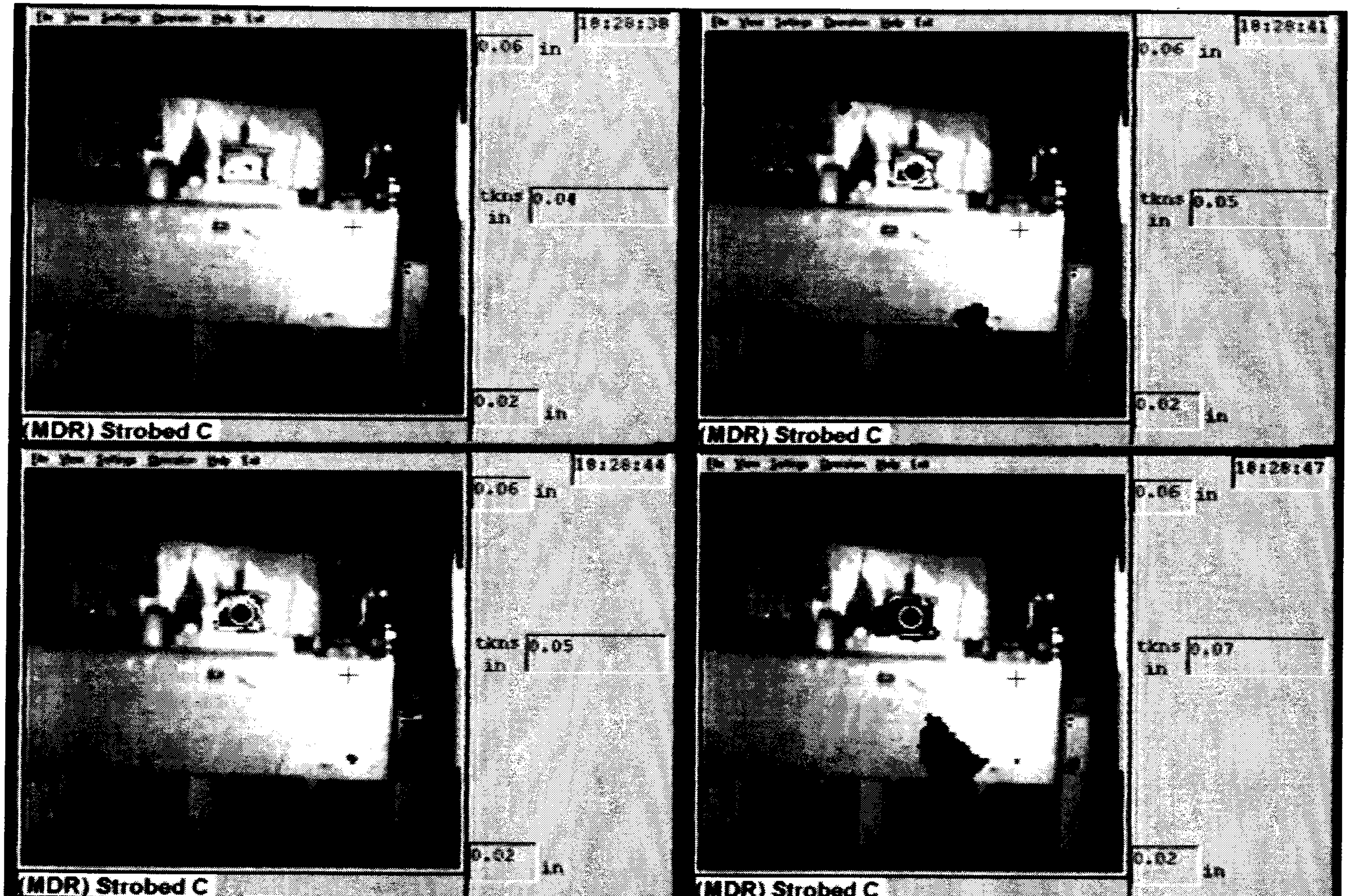


Close-up of frost/ice accumulation on LN2 container and SOFI samples

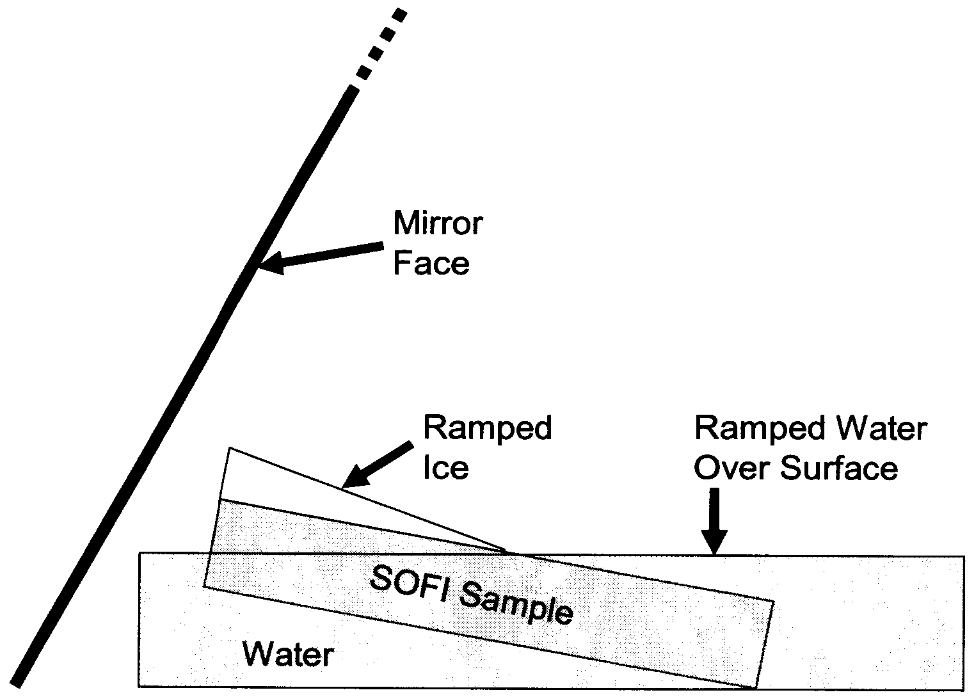
Table 1: Frost and LDI density values

Date	Temp (F)	Hum. %	Weight (g)	Density (lbs/ft3)	Foam-Ice Thickness (in) Total	Foam	Ice	Density lbs/ft3
					2X2" Area			
2/15	71	34	1.37	0.81	0.56	0.038	0.152	14.0
2/17	59	53	1.45	0.81	0.64	0.055	0.220	11.0
2/24	56	97	1.87	0.80	1.07	0.130	0.520	7.8
2/25	56	98	2.60	0.80	1.80	0.100	0.400	17.1
3/3	58	98	1.80	0.72	1.08	0.137	0.548	7.5
3/9	53	98	5.30	0.72	4.58	0.225	0.900	19.3
3/15	53	98	5.52	0.72	4.80	0.327	1.308	13.9
					5X5" Area			
3/17	50-60	98	23.00	6.91	16.09	0.140	2.226	27.4
3/17	50-60	98	23.00	6.91	16.09	0.360	5.725	10.7
3/17	50-60	98	23.00	6.91	16.09	0.330	5.248	11.6

Goal 1: Detection of LDI and Frost: MDA Images



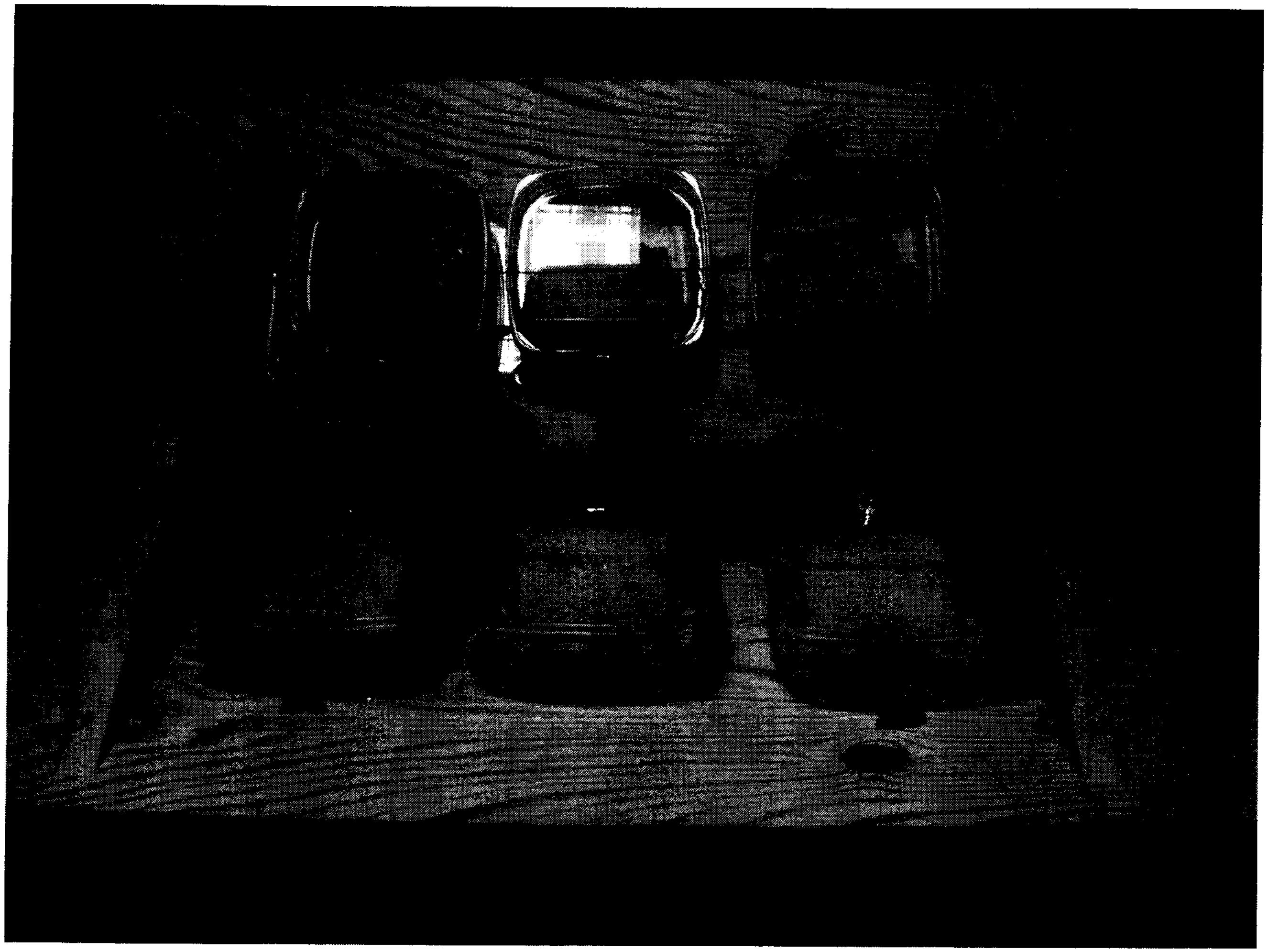
Goal 2: Determine if the MDA system can distinguish between ice and cold water on SOFI samples and whether water composition has any effect



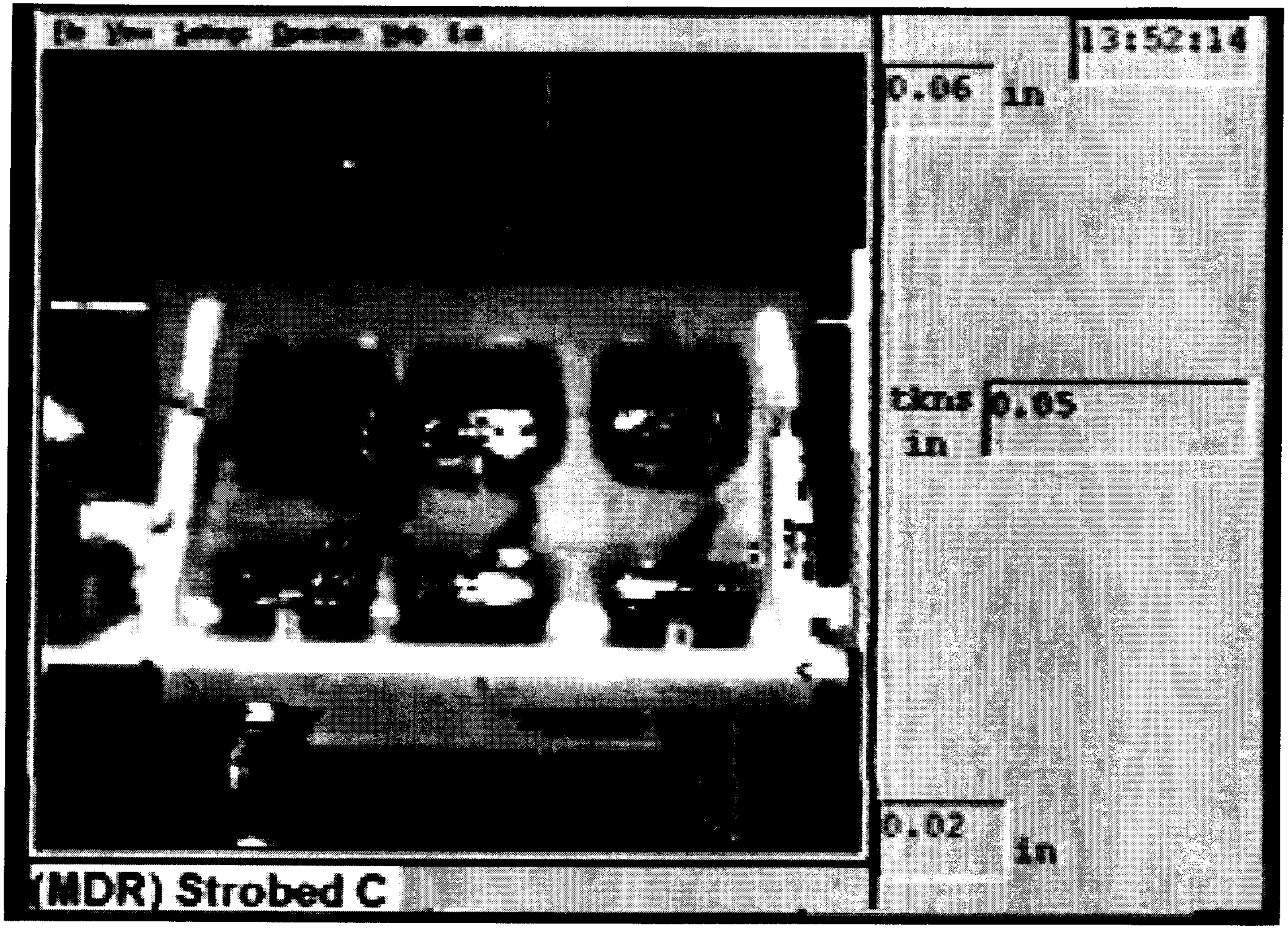
Goal 2 – Ramped Ice/Water Diagram

Schematic drawing of goal 2

Goal 2: mirror sample setup (note: close-upwire ice/water border marker)



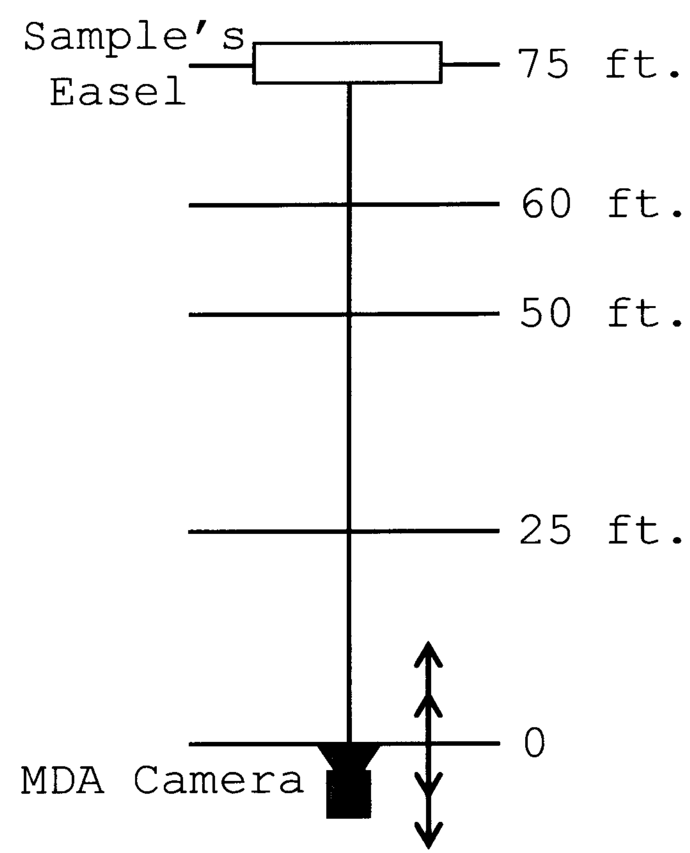
Goal 2 MDA image



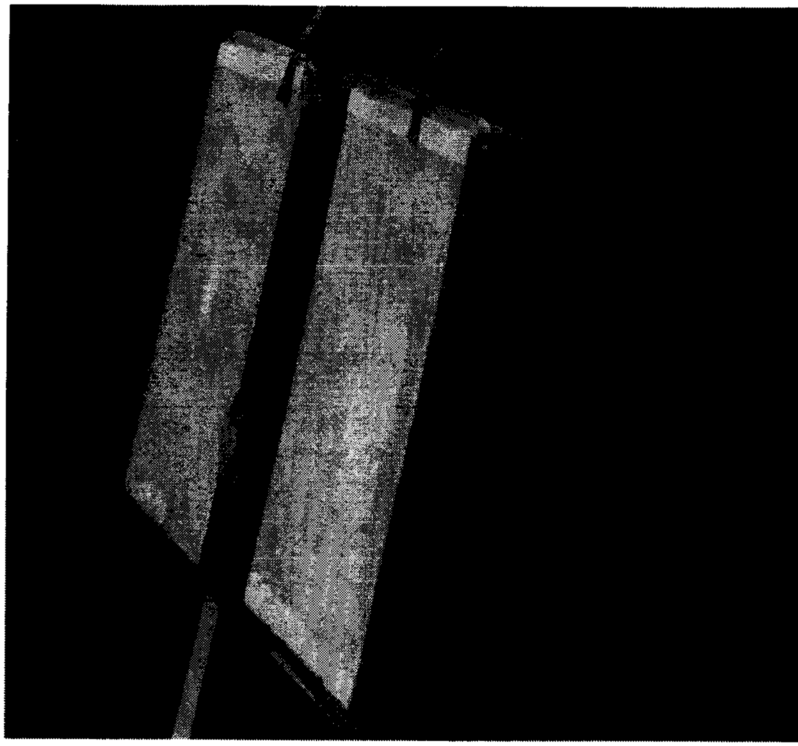
Goal 3: Determine if the MDA system can detect and measure ice thickness greater or less than 0.0625" (1/16 inch), and whether it is range independent.

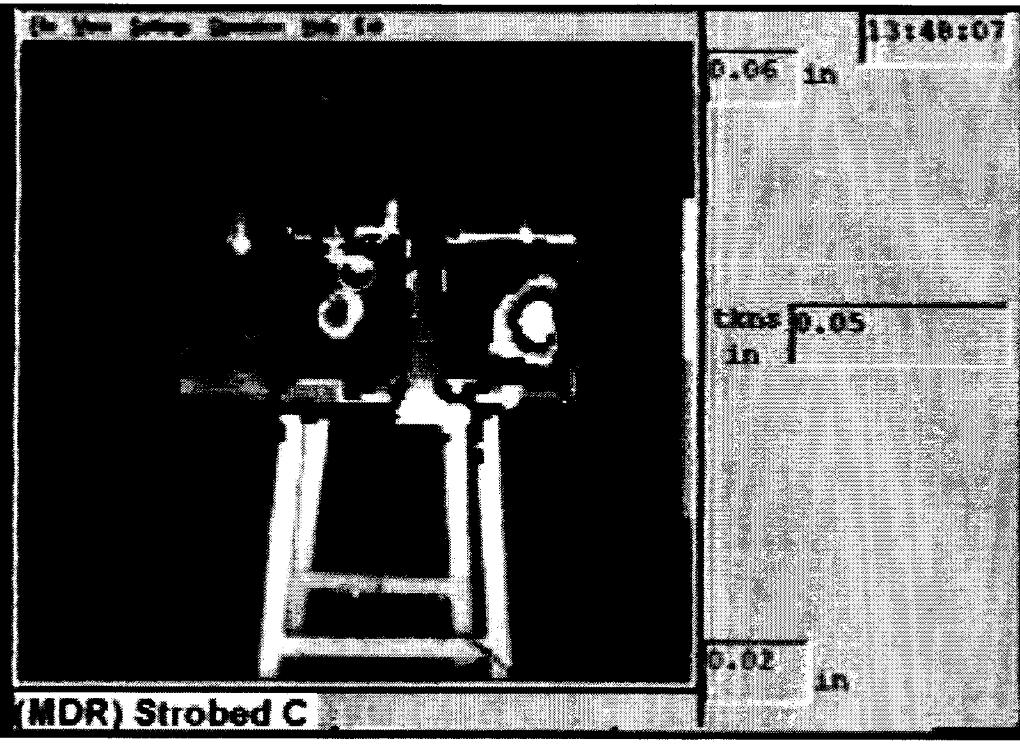
- The 0.0625 inch threshold LCC is important (as mentioned earlier) for a "go--no go" launch decision because of the danger of falling ice to flight crew windows, orbiter thermal tiles, or Reinforced Carbon-Carbon (RCC) panels.
- NASA-KSC's launch pad configuration and sensor mounts dictated about a 25 to 75 foot range for T-3 hour ice team examination.
- With concurrent on-going goal 1 testing showing difficulty in forming LDI (see goal 1 above), tests would be performed with NDI as formed from the freezer.
- The MDA system was shown to be ice density dependent in its estimate of ice thickness, and therefore these results with NDI are only exemplary, at best.
- In the beginning stages of testing, it was realized that the milled 1 in. wide steps in our the 5 x 5 inch samples were too small (approximately one inch wide) for the MDA system to resolve the small regions of interest at the ranges beyond 25 feet.

Goal 3: Schematic of the range test

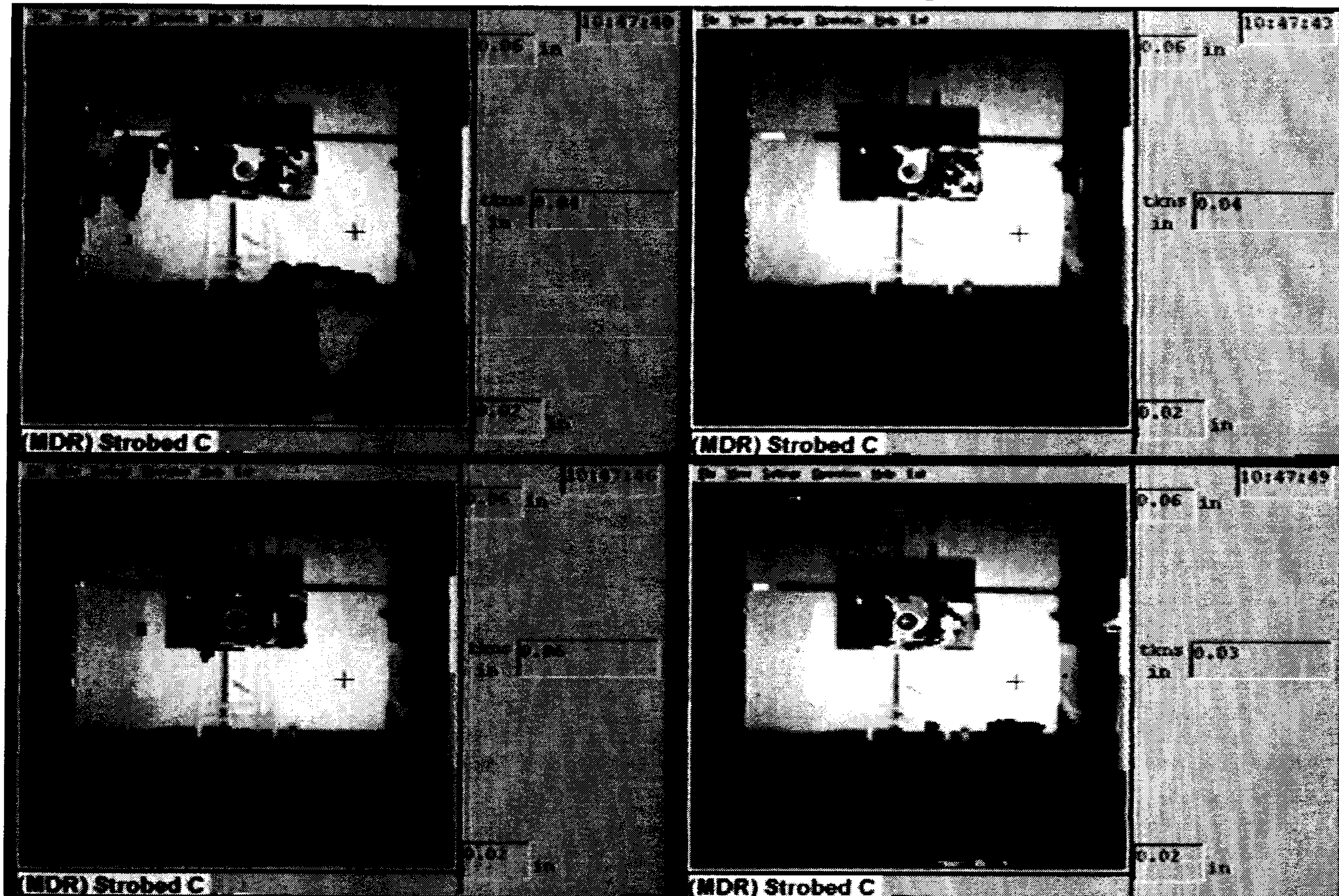


Goal 3: Photo (left) 2B & 3B milled samples with melting, corresponding MDA image (right)

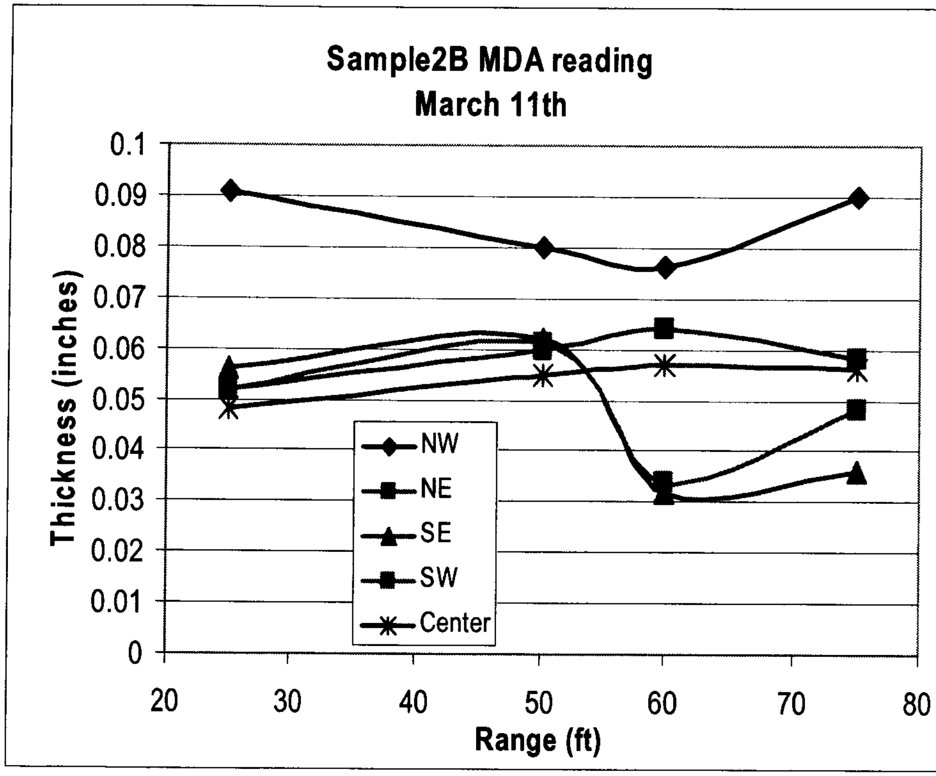


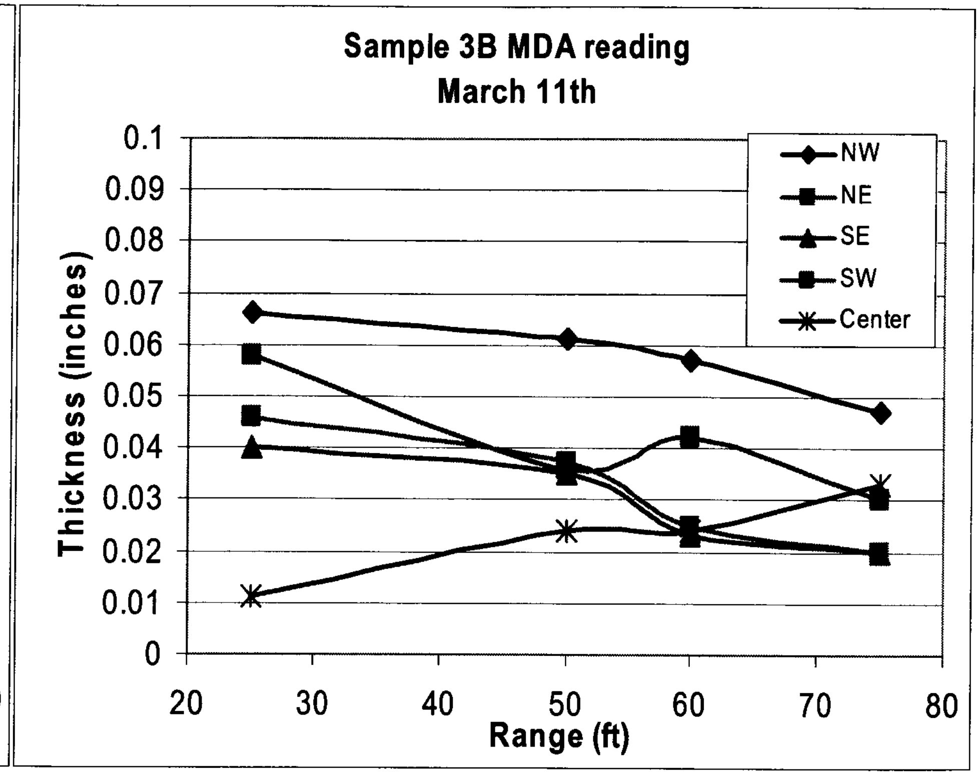


Goal 3 - range 50 ft. (3/17/05) MDA image series (read left to right, row-wise)



Goal 3: MDA system data for sample 2B and 3B on March 11th measurements from close to far range

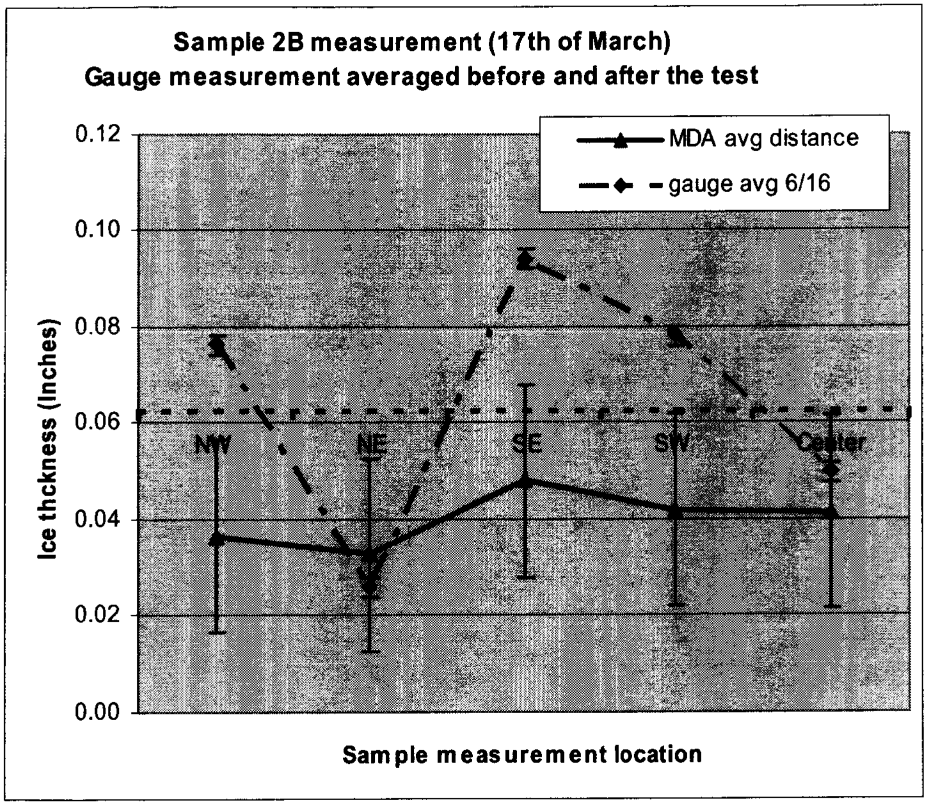


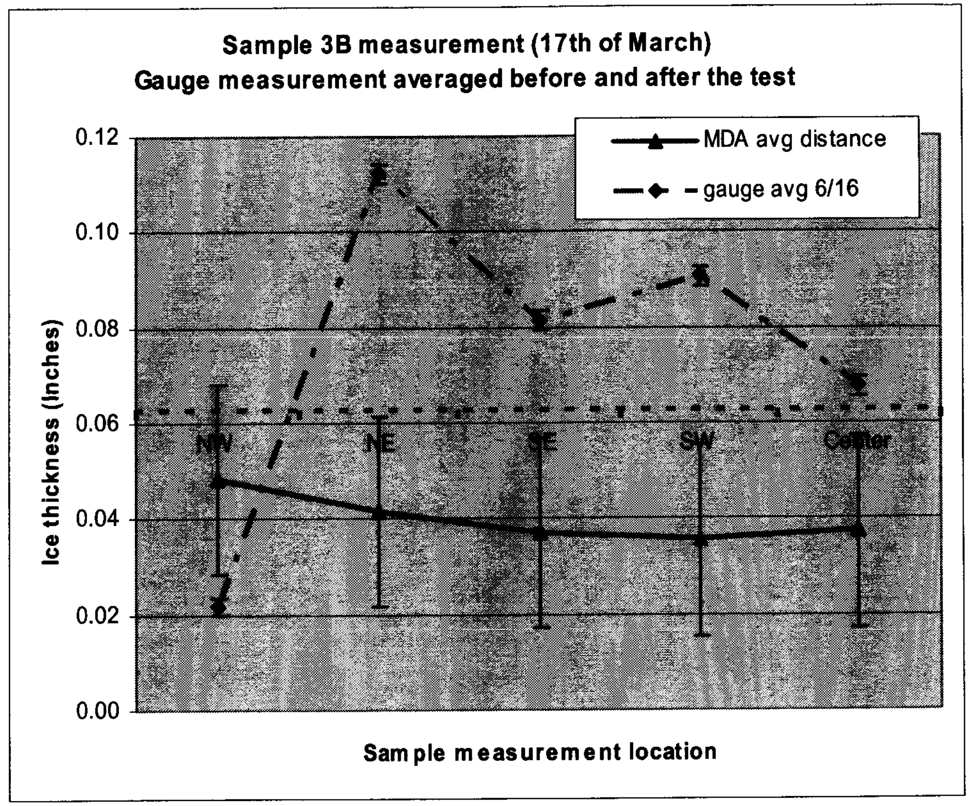


Goal 4: Determine the accuracy of the MDA system's ice thickness estimation

- Due to the similar nature of this goal and Goal 3, these tests were performed concurrently, and similar assumptions are identified.
- As in Goal 3, a dial indicator gauge was used to determine ice thickness. As mentioned previously, the accuracy of the dial gauge measurements is estimated to be ± 0.007 inch.
- The MDA system variability's include: a) an expanding sensor averaging area with increasing range, b) the reduction in intensity of Xenon strobe light with range, c) the overall uncertainty of the system being ± 0.02 inch as stated by MDA.
- Determine: Verify MDA system results as compared to actual ice gauge measurements and determine ice thickness accuracy.
- As this goal was done concurrently with Goal 3, the same samples and experimental procedures were used.

Goal 4: Average ice thickness measurements, with error bars, for the MDA system and dial gauge





Samples 2B and 3B March 17

In summary, the four test goals results were:

- Does the MDA system detect low-density ice (LDI), and if so, how does it compare to normal density ice (NDI)? *The MDA system was found to detect LDI and frost. The thickness of LDI was underestimated. The MDA system was shown to be ice density dependent in its estimate of ice thickness.*
- Can the system determine the presence of ice on SOFI irrespective of the water composition of the ice, and can it discern between ice and cold water? *The MDA system consistently distinguishes between ice and cold water, independent of whether the ice was made from distilled water, Michigan rain water, or tap water. Water composition was not seen to effect ice detection.*
- Can the system detect and measure ice less than or greater than 1/16 inch, and is the estimation of ice thickness range independent? *Evidence indicates that the MDA system can identify ice less than or greater than 1/16 inch. The system showed a lack of consistency in ice thickness measurements. The empirical evidence, at this time, indicates the MDA system is not able to accurately estimate ice thickness independent of range (i.e. as range changes, so do the thickness measurements).*
- What is the accuracy of the system's ice thickness estimation? *Empirical tests indicate the system is not accurate in its ice thickness measurements. Inconsistency, inherent noise, melting ice, and sample measurement problems prevented a satisfactory data analysis. Without additional testing, it should be concluded that the current MDA system should be used qualitatively, rather than quantitatively.*